Spacecraft Propulsion Applications for Field Emission Cathodes

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ABSTRACT

Many small-scale spacecraft propulsion systems under development could benefit from a compatible FE cathode. These thrusters challenge the performance of FE cathodes because the plasma environment they create could significantly limit the cathode lifetime if it does not have a compatible configuration and materials. The thruster current requirements and cathode integration challenges are discussed in this article. Cathode configurations are recommended to improve the cathode and thruster compatibility. Preliminary results are presented from the first successful test of an electric thruster with a Spindt-type FEA cathode.

INTRODUCTION

There is considerable interest now in microscale spacecraft to support robotic exploration of the solar system and characterize the near-Earth environment. Three classes of microscale spacecraft have been identified: Class I (5-20 W, 5-20 kg, 0.2-0.4 m), Class II (1-5 W, 1-5 kg, 0.1-0.2 m), which is sometimes referred to as nanoscale spacecraft, and Class III (<1 W, < 1 kg, <0.1 m), which is also referred to as picoscale spacecraft [1]. Microscale spacecraft will enable the development of multiple, distributed spacecraft systems to perform three-dimensional mapping of fields and particles with a resolution and flexibility unobtainable with a single, larger spacecraft. In addition to the mapping of tensor fields, microscale spacecraft mission scenarios have been envisioned where, rather than launching a single large spacecraft, the mission is accomplished by a fleet of several smaller microscale spacecraft, with the scientific payload distributed among the micro-craft to reduce mission risk. Loss of one of these spacecraft would not jeopardize the entire mission. A fleet of several microscale spacecraft, possibly in connection with a larger "mother"-spacecraft, could also increase mission flexibility. Smaller micro-craft could be placed on different trajectories around the target planet and provide an almost instantaneous, global survey of the target. A mother-craft could also release smaller micro-craft to perform high-risk operations. In one example, a close-up investigation of Saturn's ring objects has been envisioned with a swarm of microscale spacecraft descending into the ring environment while the mother-craft, providing high-data rate communication to Earth via a large high-gain antenna, may cruise at a safe distance.

The fuel savings from the use of high specific impulse (thrust/propellant flow rate>1000 s) electric propulsion systems enables more difficult planetary missions with smaller launch vehicles, a critical capability in today's environment of cost-constrained space exploration missions. Low required propellant mass will reduce overall spacecraft size and weight and high-specific impulse electric propulsion technology thus represents an obvious design approach for microscale spacecraft. The challenge is to arrive at a working, miniature electric propulsion system which can operate at much lower power levels than conventional electric propulsion hardware, and meets the unique mass, power, and size requirements of a microscale spacecraft. In addition, this technology may be used for ultra-fine attitude control on larger spacecraft, such as future interferometry missions or future inflatable spacecraft. These spacecraft will be required to offset solar disturbance torques, requiring nano-Newton thrust control resolution. In the case of inflatable spacecraft, like those proposed for mission concepts such as Arise and Space Solar Power, these propulsion modules may have to be integrated with the inflatable structure itself, necessitating the need for small, extremely light-weight propulsion systems. Micro-electromechanical systems (MEMS)-based technologies including thrusters, valves, and control electronics may be integrated into a single chip or a 3-D stack of chips. Larger scale inflatable spacecraft will also require mesoscale Hall or ion thrusters which provide 1-10 mN of thrust at power levels < 300 W with discharge chamber diameters smaller than 50 mm (Hall thrusters) or 60 mm (ion thrusters).

Many electric thrusters being miniaturized require a cathode to provide electrons for propellant ionization and/or ion beam neutralization. The positive ion beam emitted by the thruster must be accompanied by an electron beam to prevent spacecraft charging. Electrostatic thrusters are being developed to operate between 10s of mW and 500 W. For the small scale size and power objectives for electric propulsion system miniaturization, FE cathodes have demonstrated much higher efficiency, smaller dimensions, and lower system complexity than filament and hollow cathodes. Filament, thermionic, and hollow cathodes require heaters, keepers, and propellant feed systems which place lower limits on their power and size scalability. Filament cathodes consume 0.1 –100 W/mA [2,3] in heater power with lifetimes severely limited by large coupling voltages and thermal cycling. Thermionic cathodes typically consume 1.5-2 W/mA in heater power [4]. State-of-the-art 1/8" hollow cathodes have demonstrated 50 mA with 0.2 mg/s of xenon and 8 W consumed by the keeper electrode with an anode voltage of 15 V (0.2 W/mA) [5]. Additional power is required by this cathode in heating the thermionic emitter. This power requirement can more than double the operating power on start-up. Efficiency of these cathodes increases with current as cathode self-heating becomes more effective. A hollow cathode has demonstrated 700 mA at 0.08 mg/s with no power consumed by the keeper electrode and no heater power during operation with a thruster [6]. This same cathode requires 0.05 mg/s with 14 W (0.7 A, 20 V) consumed by the keeper electrode during stand-by (0.02 W/mA). Proposed orificed hollow cathode designs are expected to be capable of 100 mA emission with 0.1 mg/s and 7 W consumed by the keeper electrode (0.07 W/mA). A cesium hollow cathode which demonstrated 10 W/mA, has been used with cesium field emission electric propulsion (FEEP) systems [7]. The disadvantages of these cathodes include power-consuming conditioning procedures before start-up, stand-by operation, heaters, and keepers. In contrast, a FE cathode has demonstrated 120 mA at <1 mW (< 8 μW/mA) consumed through the gate electrode with no propellant or heating required. Each of these cathodes consumes additional power in coupling with the ion beam to neutralize it. Hollow cathodes couple to plasmas very efficiently because they generate their own plasma environment. The coupling power of the other cathode options depends on the their environments. Considering the coupling power required, it is anticipated that a FEA cathode will operate at ~0.056 W/mA. This estimate is based on the assumption that 100 mA (at 100 mA/cm^2) is emitted at a gate electrode voltage of 36 V with 20 V coupling between the gate and plasma with ion number densities of 8×10^8/cm^3 and plasma electron temperatures of 5 eV. The cathodes have not yet been tested with electric propulsion systems, however this process has been modeled to predict these results [8]. Some microscale spacecraft proposed will have less than 100 mW of power. Compatible FE cathodes may enable the use of microscale EP systems on these spacecraft.

In the following sections of this paper, the approach to integrating these technologies is discussed and some recent progress is presented. Meso- and microscale thrusters which could benefit from a compatible FE cathode, the cathode requirements, and the cathode environment in these systems are described. Cathode candidates which currently seem to be the most compatible with EP systems and required advances in FE cathode technologies are also discussed. Recently acquired results from integration experiments are presented.

ELECTRIC PROPULSION SYSTEMS

In this section, the configuration and performance of several meso- and microscale electric thrusters are described, the cathode performance requirements are presented, and the cathode environments are discussed. Mesoscale ion and Hall thrusters have the advantage of higher thrust levels and an inert propellant. Colloid and field emission thrusters have the advantage of scalablility in size and power to be compatible with microscale spacecraft. Many of the mesoscale and microscale thrusters being considered are still under development; the performance of larger systems are discussed in this section with performance objectives for the miniature systems. It is obvious that the performance of each of these systems will be significantly improved with a compatible FE cathode. Tables are presented at the end of the section describing the performance of state-of-the-art systems, the cathode environment, and state-of-the-art cathode performance.

Mesoscale ion engines

An ion engine has three major components as shown in Figure 1: (1) the discharge chamber, (2) the ion optics and (3) a neutralizer cathode. Propellant injected into the discharge chamber is ionized by electron bombardment in a low pressure discharge. Permanent magnets oriented axially near the anode trap the electrons and impede their flow to the anode. The ion optics are composed of two multi-aperture grids which are biased to accelerate and focus ions which drift into the interelectrode gap. The neutralizer cathode produces electrons to neutralize the ion beam. Modeling has shown that the ionization efficiency of the discharge chamber is unacceptably low if the device scale is too small, primarily because the higher surface-to-volume ratio results in excessive plasma losses to the walls. Current research is therefore focused on mesoscale thrusters with MEMS components, rather than microfabricated engines.

Ion engines have been optimized and flight qualified to operate at power levels up to 2.3 kW. Mesoscale ion thrusters were developed to operate on cesium with considerable success; however, xenon propellant is preferred over cesium because of its toxicity. Cesium ion thrusters have demonstrated 12 μN at 4.58 W from a 1.27 cm-diameter discharge chamber up to 5.3 mN at 237 W from a 4.58 cm-diameter discharge chamber [9]. At low power levels, the thermionic cathode consumed as much as 48 % of the total power consumed by the thruster. More recently, the performance of a xenon ion thruster with a 5 cm-diameter discharge chamber was reported as 2.2 mN and 2300 s at 49% thrust efficiency and 50 W of power [10]. The efficiency calculation does not include the power and propellant consumption by the cathode. The reported performance of the 5-cm thruster is described in Table 1. The development approach currently being implemented relies on a conventional electron bombardment discharge chamber with xenon propellant, field emitter cathodes, conventional chemically-etched metal grids or MEMS grids [11] and a field emitter neutralizer. The mesoscale engines being developed will have discharge chambers 1 to 5 cm in diameter and will operate at power levels of 10 to 300 W. The desired operating characteristics are an exhaust speed of 36 km/s (specific impulse of 3600 s), thrust levels of 0.5 to 5 mN, an efficiency of 50 % at 300 W, and lifetimes of up to 6000 hours.

A FE cathode compatible with an ion thruster could significantly improve the system efficiency. The anticipated requirements on a discharge cathode is emission of up to 1 A (100-200 mA/cm^2) reliably over 6000 hours into xenon gas with a pressure of up to 10^{-4} torr and a plasma density of 10^{11}/cm^3. The neutralizer cathode must also operate for over 6000 hours and be capable of emitting up to 40 mA in the environment near the exit plane of the thruster, where xenon gas pressures may be as high as 10^{-5} torr and the charge-exchange ion current densities should be less than 0.004 mA/cm^2. The charge-exchange ions will be accelerated through approximately 20 V between the plasma and the cathode gate electrode.

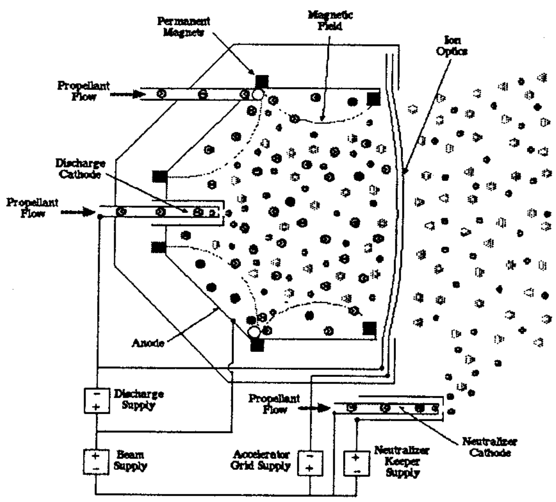


Figure 1. Ion thruster configuration.

Mesoscale Hall thrusters

A Hall thruster is an electrostatic propulsion device which also ionizes the propellant by electron bombardment, like ion thrusters. A cross-section of a Hall thruster is shown in **Error! Reference source not found.**. Propellant is injected through the anode into the discharge chamber. A single cathode is used to emit electrons which ionize the propellant and neutralize the ion beam. The potential applied between the anode and cathode creates an axial electric field to accelerate the ions. Inner and outer electromagnets create a radial magnetic field with large gradients near the physical exit plane of the thruster. The electrons enter the discharge chamber and become confined by the magnetic field in an azimuthal drift towards the anode. Propellant is ionized in the electron cloud. The ions are primarily accelerated in the discharge chamber by the axial electric field to generate thrust. Because of the high electron density in the ionization and acceleration region, the ion current density is not space-charge limited like the ion thruster. Therefore, Hall thrusters can deliver the same thrust from a more compact system with a higher thrust density.

Hall thrusters have been optimized to operate at 1.5 -3.0 kW and are currently being scaled down to mesoscale systems which will be optimized to generate 1-10 mN of thrust. Higher pressures, current densities, and magnetic field strengths are then required to reduce mean free paths in the discharge chamber and maintain the plasma discharge as the size of the thruster is reduced [12]. The X-40 [13], D-32 [14], and a 50 W [12] Hall thruster fall into the mesoscale thruster category. Xenon is the preferred propellant for these systems because of its high mass, relatively low ionization energy, and inert nature. The X-40 has a 40 mm discharge chamber diameter. Its performance was reported as 7.43 mN of thrust at 100 W (150 V, 0.67 A) and 0.74 mg/s to generate 1020 s specific impulse (ion velocities of ~10.2 km/s) at 37 % efficiency (not including the cathode power and propellant). At 200 W and 14.5 mN, the thruster efficiency reported was 48 %. The lifetime of this system was projected to be 850 hours. It might be increased up to 2000-3000 hours by employing more sputter resistant materials. The D-32, with a 32 mm diameter discharge chamber demonstrated 4.3 mN at 75.6 W (120 V, 0.63 A) and 0.6 mg/s at 20 % efficiency. At 172 W (200V, 0.88 A) and 0.9 mg/s, the D-32 operated at 27 % efficiency. The D-32 and X-40 both used electromagnets to facilitate magnetic field optimization at each operating point. Permanent magnets were used in the 50 W thruster developed with a 3.7 mm discharge chamber because of its small size and potentially high operating temperatures of the electromagnets. While medium scale Hall thrusters with 100 mm discharge chamber diameters require magnetic fields of 300 Gauss, the 50 W thruster required magnetic fields exceeding 5000 Gauss. This thruster operated at 100 W (250 V, 0.38 A) and 0.021 mg/s to generate 773 s at 6 % efficiency. The performance of this thruster was limited, in part, by the magnetic system used. The magnetic field configuration could not be optimized at each operating point and the high operating temperature of the thruster could have affected the performance of the magnets. The thrust efficiency also tends to decrease with decreasing discharge chamber diameter.

According to the results received, miniaturization of the Hall thruster seems to be limited to a 40 mm discharge chamber to achieve at least 30 % efficiency. These thrusters were tested with a hollow cathode and the thruster performance described does not consider cathode power and propellant consumption. Consideration of the hollow cathode performance also decreases the efficiency of the system by several percent.

A field emission cathode compatible with a Hall thruster could significantly improve the performance of the mesoscale propulsion systems. The lifetime of an X-40 with improved materials should be 2000-3000 hours, therefore the same cathode lifetime will be required in the cathode environment. The cathode current requirement ranges from 0.1 to 1 A. The current density objective is 100 mA/cm^2.

The cathode environment of a Hall thruster consists of xenon neutrals and ions. One of the xenon ion populations near the cathode originates from charge-exchange collisions between ions in the thruster ion beam and ambient neutrals. The xenon pressure near the cathode depends on propellant flow rate, thruster performance, and vacuum chamber pumping speed. During ground testing of an X-40, this pressure should range between 10^{-6} and 10^{-5} Torr. The charge-exchange collisions produce fast neutrals and slow ions. The slow ions are then accelerated by local electric fields which can direct them towards the cathode. These ions will then bombard the cathode emitting surface after being accelerated through 20 V in addition to the voltage difference between the emitting surface and the gate electrode. The characteristics of these species have not been quantified; however ion current density, J_i, estimates can be made by scaling measurements made on larger systems with discharge current [15,16]. It is estimated that the charge-exchange J_i will be approximately 2.2 $\mu A/cm^2$ at a thruster discharge current of 0.5 A and local pressure of $2x10^{-5}$ Torr, based on current scaling from measurements taken in the environment of a 70 mm Hall thruster [15].

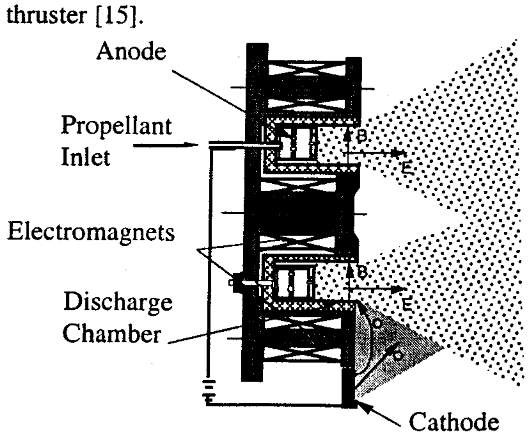


Figure 2. Hall thruster configuration.

Meso- and microscale FEEPs and I-LMISs

Field Emission Electric Propulsion (FEEP) and Indium Liquid Metal Ion Source (I-LMIS, also referred to In-FEEP) systems also accelerate ions electrostatically to generate thrust; however, unlike the ion and Hall thrusters, the propellant is not ionized by electron bombardment; the propellant is field ionized. FEEPs use cesium and I-LMISs use indium liquid metal propellant which is fed by capillary forces from the propellant reservoir through a small channel (FEEP), or wicked up the outside of a needle from the propellant reservoir (I-LMIS). The emitters are terminated with sharp edges and biased positively with respect to an extraction electrode located downstream of the emitter. The Cs-FEEP slit emitter configuration is shown in **Error! Reference source not found.**a, and the In-FEEP configuration is shown in Figure 3b. The electric field applied between the electrodes increases the surface charge density which causes a deformation of the surface of the liquid metal into Taylor cones with a cusp (often called a jet) to maintain equilibrium between electrostatic and surface tension forces [17]. The cusps cause geometric field enhancement, which further reduces the radius of curvature of the tip of the cusp, and in turn, further increases the electric field at the tip. When the electric field strength reaches 10^7 V/cm, atoms of metal on the tip are ionized by field ionization or field evaporation. Liquid metal is converted into an ion beam without the transitional vapor phase. Electrons are collected by the emitter and channel walls and ions are accelerated by the applied electric field through the slit in the extraction electrode which doubles as the acceleration electrode. FEEPs are now fabricated with a slit geometry to increase the throughput. The slit width is typically ~1 μm. The gap between the channel and extraction electrode is ~1 mm. The applied voltage between the electrodes is typically 9 kV. The thrust can be throttled by adjusting the applied voltage to control the beam energy and ion generation rate.

The performance of this system depends on emitter geometry, electrode configuration, propellant, and applied voltage. Cesium and indium are preferred propellants because they have low ionization potentials, high atomic masses, effectively wet metal surfaces, and offer compact storage on spacecraft as solids. One system or propellant has not yet demonstrated superiority. The lower vapor pressure of indium results in a lower propellant leak rate. The less reactive nature of indium results in a more robust system which does not require special handling on the ground to prevent contamination by the environment. Cesium melts at a lower temperature, therefore less heater power is required for the FEEP. Indium Liquid Metal Ion Sources (LMIS) have been used for spacecraft potential control and are now being developed for propulsion applications also [18]. They are being developed to operate at 10s of μN and 4.5-6.5 kV, >6000 s specific impulse at ~15 μN/W (67 W/mN). Cesium FEEP systems have been developed to operate at 66 W/mN for 40 μN of thrust at 9000 s specific impulse (~90,000 m/s ion velocities) with 2.7 W of power. Larger FEEPs have demonstrated 1400 μN at 9000 s and 93 W. The thrust level depends on the emitter (extraction) electrode voltage and slit length. A FEEP with a 2 mm-slit produces 40 μN with 5.5 kV on the emitter electrode and –5 kV on the acceleration electrode while a 70 mm slit has demonstrated 1.4 mN at the same operating voltages [19].

Miniature field ionization ion sources have been demonstrated with arrays of volcano-shaped ion emitting cones similar to Spindt-type field emitter electron sources [20,21]. Arrays of these gated cones have been microfabricated with 1.5 μm cone heights with 1 μm apertures in the cones and 15 μm apertures in the gate electrodes. They have been fabricated with 106 volcano tips/cm^2. The advantage of this configuration is that the thrust and specific impulse could be independently controlled by addressing only segments of the arrays. This thruster configuration will also be more compact and lightweight than the larger systems; therefore it will be more compatible with microscale to picoscale satellites. The challenge with this system is maintaining high propellant utilization. Microscale field ionization electric thrusters are still under development.

FEEPs and I-LMISs require an electron source only for ion beam neutralization. Hollow, thermionic, and filament cathodes have been used with FEEPs. A cesium hollow cathode demonstrated 10 W/mA [7]. FE cathodes have demonstrated much higher efficiencies in UHV environments. The FEEP cathode is required to deliver up to several milliamperes in the cesium environment. Both Cs ions and neutrals will interact with the cathode to affect its performance. While it has been demonstrated that cesium improves the performance of FE cathodes, it will reduce emission stability. Experimental and theoretical results have shown that the charge-exchange back-flow ion current is 1 % of the beam current [4]. With a beam current of 0.9 mA, the plasma density was reported to be 2.4×10^8. The charge-exchange current density to the cathode region was calculated to be 0.2 μA/cm^2, and then scaled with beam current for the estimates shown in Table 1. In this system, it has been shown that the energy of singly charged ions bombarding the cathode could be as high as 100 eV [4].

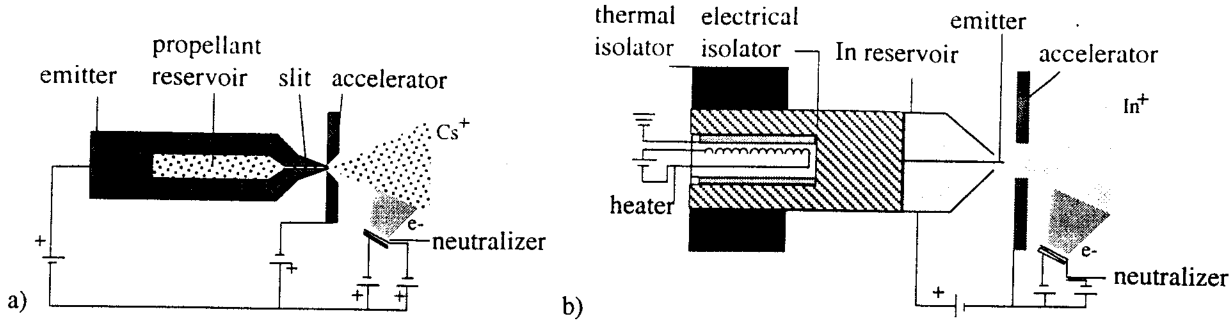


Figure 3. a) Cs-FEEP slit emitter configuration and b) In-FEEP needle emitter configuration.

Meso- and microscale colloid thrusters

Colloid thrusters are similar to FEEPs except that charged droplets, instead of atomic ions are emitted and accelerated [22,23]. An electric field is applied between the capillary tubes feeding the propellant and the extraction electrode to increase the surface charge density in the liquid. At the critical surface charge density, the unstable surface forms a cone-jet configuration [24]. Incipient droplets are polarized and ruptured into two portions of net charge [25]. One portion remains at the tip and the other escapes from the fluid and is accelerated by the electric field. The droplets are either positively or negatively charged depending on the propellant used. A bipolar thruster employs both positively and negatively charged droplets [22]. Operating in this mode, the thruster is self-neutralizing. The fluid used in a colloid thruster has a much higher surface tension than the fluid used in FEEPs, primarily generating charged colloids instead of atomic ions. Non-conducting fluids are typically doped to increase conductivity and colloid emission frequency. A high and uniform specific charge (coulomb per droplet mass) is optimal to maximize the specific charge efficiency and specific impulse. If electric field strengths, fluid conductivity, and propellant flow rates are too high, droplet streams with a large distribution of droplet charge-to-mass ratios (low specific charge efficiency) are created.

The performance of colloid thrusters depends on the propellant, the capillaries, and the applied electric field. High solvation capability, low vapor pressure, low freezing points, and low corrosivity are desired attributes of the propellant. Glycerol is a commonly used propellant. Glycerol doped with sodium iodine produces positively charged droplets. Glycerol doped with sulfuric acid produces negatively charged droplets. Platinum capillaries provide high resistance to corrosion, maximizing thruster lifetime. Bipolar colloid thrusters were developed with platinum capillaries having 200 μm inner diameters using sodium iodide and sulfuric acid doped glycerol propellants. They produced thrust between 0.2 and 0.5 mN at power levels of about 4.4 W/mN, requiring voltages of 4.4 and -5.8 kV, depending on droplet polarity [22]. Specific impulses between 450 and 700 s were estimated. Specific impulses up to 1350 s have also been obtained at 0.55 mN thrust [26]. Current levels are on the order of 10-100 μA.

Colloid thrusters have not yet been miniaturized, but miniaturization has been proposed. These thrusters are natural candidates for miniaturization because the high electric fields required for charged droplet emission can be obtained at reduced voltages with reduced dimensions. However, high accelerating voltages (~10 kV) will be required to attain a specific impulse near 1000 s. It should be possible to operate these thrusters at milliwatt power levels and integrate them into stacked chip structures for microscale spacecraft.

When a colloid thruster is operated in biploar mode and emits only a positive stream of ions, a charge neutralizer will be required. An electron source must be used which operates at power levels comparable with 4.4 W/mN thruster performance. Filament and hollow cathodes operate at higher powers than this thruster at the required current levels of approximately 0.1 mA. A field emission cathode could easily provide 0.1 mA at much lower power levels, however, the cathode must tolerate the thruster environment with minimal effect on performance for > 4000 hours. The colloid thruster will generate a fairly hostile environment as colloids may be deposited on the cathode. The pressure in the cathode region and ion flux to the cathode depend on the vacuum chamber pressure and performance of the thruster. This environment has not yet been characterized.

Table 1. Representative performance and cathode environment of meso- and microscale propulsion systems.

	Mesoscale Ion Thruster (5 cm)[10]	**Mesoscale Hall Thruster (X-40)[13]**	**Mesoscale FEEP Thruster [19,4]**	**Mesoscale Colloid Thruster[22]**
Thrust (mN)	2.2-4.7	5-32	0.0001-2	0.2-0.5

Power (W)	50-116	80-510	2.7-93	0.88-2.2
Power/Thrust	23	16	66	4.4
Specific Impulse (s)	2,300-3,100	1,160-1,933	6000-11000	450-700
Current (mA)	230-430 (discharge) 44-81 (neutralizer)	500-1,700	0.25 (0.05 mN) 0.5 (0.1 mN)	-
Efficiency	0.49-0.61	0.31-0.55	0.98	0.50-0.78
Thruster Specific Mass (kg/W)	-	-	0.008	-
Propellant	Xenon	Xenon	Cesium	Glycerol
J_i(μA/cm^2)	4,000 (discharge)27 0.004-0.008 (neutralizer)	2 -7	0.002-2	-
Pressure (Torr)	10^{-3}-10^{-6}	10^{-6}-10^{-4}	10^{-6}	-
Lifetime (hours)	6,000	950 (demonstrated), 2000 (possible)	450-20,000	4,300

INTEGRATION CHALLENGES

The primary concerns with integrating FE cathodes with EP systems are space-charge limited emission and cathode lifetime in the plasma environments generated by the propulsion systems. An additional concern is the sensitivity of the tip work function and conductivity to the environment. Typically FE cathodes are operated in a close-spaced triode or diode configuration with one electrode as the anode. In an EP system the FE cathodes will have to operate in a diode configuration with a gate electrode and the local plasma providing a virtual anode. The space-charge current limit depends on the plasma density and temperatures, and electron beam energy and current density. The cathode lifetime will be limited because it will be subjected to constant ion bombardment which can sputter the sharp tips if the energy of the ions exceeds the energy threshold for sputtering. The self-generated ion population originates near the cathode when the electrons emitted by the cathode ionize ambient neutrals. The second ion population of charge-exchange (CEX) ions is generated near the thruster. This ion-rich environment can cause permanent changes in the structure of the emitting surface and temporary changes in the cathode work function, severely affecting the cathode performance because the performance of these cathodes is exponentially sensitive to the radius of curvature and work function of the tips. Because the cathodes will not be operating in UHV facilities with most of the thrusters, the cathodes will be subjected to higher levels of contamination which can affect the cathode work function, conductivity, and frequency of arcing events.

Table 2. FE cathode performance requirements for two thruster current regimes.

Regime	**Current Density (mA/cm^2)**	**Gate Voltage (V)**	**Current/Power (mW/mA)**	**Lifetime (hours)**
I	50-200	≤36	≤10	>6,000
II	1-10	≤20-100	≤10	450-20,000

APPROACH TO INTEGRATION

For FE cathodes to be compatible with EP systems, they must meet the current density and lifetime requirements in their environments. The fact that they do not require propellant, is a major advantage, however, to compete with conventional cathode technology, they must also consume less than 100 mW/mA through the gate electrode. The performance objectives for FE cathodes compatible with mesoscale and microscale electric propulsion systems are described in Table 3. There are two performance regimes targeted. Regime I represents the cathode performance required by the propulsion systems generating millinewton thrust levels and requiring hundreds of milliamperes of current. Regime II represents the cathode performance required by the propulsion systems generating micronewton thrust levels and requiring tens to hundreds of microamperes of current. An efficiency of at least 10 mW/mA will be required to satisfy the power limitations of picosatellites with less than 100 mW total power. The tolerable power consumption of the gate electrodes will further limit the cathode efficiency. The values in Table 3 represent the demands on the cathodes by the electric propulsion systems only. Ideally, one cathode is developed to satisfy the requirements of all of the systems, therefore, this strategy is employed. The mesoscale thrusters generate the most hostile plasma environments because of their densities, therefore cathodes will be developed for (Regime I) and tested in these environments first. The challenge at hand is to provide 50-200 mA/cm^2 for more than 6000 hours with approximately 35 V at no more than 10 mW/mA (not including the power consumed coupling to the ion beams).

The FE cathode technology which has demonstrated the highest current density, lowest operating voltages, and highest efficiency to-date is the Spindt-type field emitter array (FEA) cathode. It is also the most mature and accessible of the microfabricated FE cathodes. Less mature FE cathode technologies include thin Negative Electron Affinity (NEA) films and carbon nanotubes. Rigid carbon nanotube cathodes have not yet been grown in microfabricated gate structures, therefore the operating voltages have been greater than 100 V with efficiencies much lower than 10 mW/mA. Carbon and diamond NEA films have demonstrated turn-on electric fields which are lower than the Spindt-type cathodes and 100 mA/cm^2, however, either their operating voltages are too high or their efficiencies are too low [28,29,15]. Spindt-type cathodes have demonstrated current densities greater than 2000 A/cm^2 from Mo [30,31] arrays and 2 A/cm^2 from Si arrays [32] in UHV in triode configurations with efficiencies higher than 0.01 mW/mA and lifetimes greater than 8000 hours.

At this time it is believed that to meet the current density and lifetime requirements of the EP applications, the Spindt-type cathodes should be coupled with carbide or NEA material films. Experiments have shown that xenon will not affect the work function of Mo, Si, and C cathodes. [33] It has also been shown that the energy threshold for sputtering Mo and Si FEA cathodes with xenon ions is 49 eV and 63.7 eV, respectively [33]. The self-generated ions consist of both single and double ions if the cathode is operated above 35-37 V. At operating voltages below ~85 V, the cathode erosion process is dominated by the double ions. Mo and Si FEA cathode operating voltages will then be limited to ~37 V, approximately the double ion ionization potential of xenon, to achieve lifetimes greater than 6000 hours in a xenon environment where only the self-generated ion population is considered [33]. In the thruster environment, the charge-exchange ion population will further limit the operating voltages. This population of ions also consists of both doubly and singly charged ions. With operating voltages no higher than 37 V, the erosion process is again dominated by the double ions. This ion population will further limit the operating voltages to approximately 5 V (Mo) and 13 V (Si) because ions will be accelerated through approximately 20 V before entering the gate electrode apertures [33]. With optimistic FEA cathode characteristics including gate aperture radii of 0.2 μm, excellent uniformity, effective tip radii of 4 nm [34], and packing densities of 5×10^7 tips/cm^2, modeling results show that it is impossible to attain 100 mA/cm^2 with Mo and Si FEA cathodes operating in the plasma environment generated by a Hall or ion thruster [33]. Other cathode configurations limitations include a lower limit on cathode gate electrode thickness because of potential delamination due to excessive heating from electron current and ion bombardment in a plasma environment. The performance can be improved by coating the cathodes with a lower work function material; it is anticipated that ~3.5 eV will be required. If the coating decreases the sputter yield also, higher operating voltages may be tolerated while meeting the EP system lifetime requirements. Materials with these properties could include HfC [35] ZrC [36], and carbon [28]. Mo and Si FEA cathodes have been successfully coated with carbide and carbon films [37,38,39,40,41]. These films have significantly improved the cathode performance in current and stability in UHV and in more hostile environments. The cathode materials must also demonstrate stability in ground test facilities where the oxygen partial pressure could be ~10-7 Torr. Some temporary performance degradation from limited oxygen adsorption is tolerable if it is reversible and can be temporarily compensated by additional cathodes at little cost. Depending on the performance of the FEA cathodes with the thin film coatings, the cathode performance with these films may still not meet both the current density and lifetime requirements.

Further cathode ruggedization is recommended with an electrostatic ion filter and an arc protection architecture. An ion filter should be used to retard the flow of charge-exchange or discharge ions to the cathode microtips. Without this flux of ions, the tolerable operating voltages will increase by more than 20 V and the current by several orders of magnitude while satisfying the lifetime requirements. A current limiting architecture that electrically isolates segments of an array of tips will also extend cathode lifetime. In the hostile thruster environments the cathodes will be contaminated by cathode, thruster propellant, and facility materials. In space, micrometeroids could impact the cathode and short out tips and gates. Often this contamination results in excessively high current densities and arcing between the tips and the gate electrode. Several architectures have been recommended to limit the current through a tip to prevent arc formation. One appealing current limiting configuration is the VErtical Current Limiting (VECTL) architecture [42] because it is a passive configuration which is microfabricated with the cathode. Packing densities of 5×10^7 tips/cm^2 have been achieved with this architecture. Stable-resistivity wafers on the Si substrates could further stabilize the cathode performance. The field effect transistor configuration is another current limiting architecture option; however, this configuration could significantly reduce the packing density of the arrays of microtips. A segmented array with fuse interconnects has also been suggested to isolate damaged array segments from the larger integrated array. [43]

RECENT PROGRESS

Very promising results have been obtained recently during experiments to demonstrate the compatibility of these cathodes with electric propulsion systems and their environments. It was shown that a Mo FEA cathode performance would only degrade temporarily while operating in 10^{-5} Torr of xenon the gate voltage is only 37 V. It was demonstrated that the performance of a ZrC/Mo FEA cathode was more stable in primarily xenon environments than Mo FEA cathodes. The Mo FEA cathode was fabricated at SRI International with 50,000 tips in a 1-mm diameter circular pattern. The gate apertures were on 4 µm centers with 0.9 µm diameters. The ZrC coating was deposited on the array of tips at Linfield Research Institute. The results from this experiment are shown in Fig###. These data are preliminary. In the near future, we will repeat this experiment with similar cathodes.

For the first time, field emission cathodes were used with a FEEP for positive charge neutralization. A 50,000 tip Mo Spindt-type FEA cathode from SRI Int. and a carbon nanotube field emission cathode from FEPET demonstrated positive ion charge neutralization of an In-FEEP thruster. The thruster was developed at Austrian Research Center Seibersdorf. One objective of the experiments was to demonstrate that a FE cathode could operate with a FEEP and provide charge neutralization of the thruster. The thruster and cathode were electrically floating during the experiments to show that the floating potential of the thruster could be zeroed with the neutralizer electrons. The electrical schematic employed in the experiments is shown in Figure 4. Data from these experiments are shown in Figure 6 & Figure 7. The second objective of the experiments was to determine the performance improvements introduced by the FE cathodes. A comparison of the performance of the thruster with each of the cathodes tested is shown in tages, and floating potentials.

Table 3.

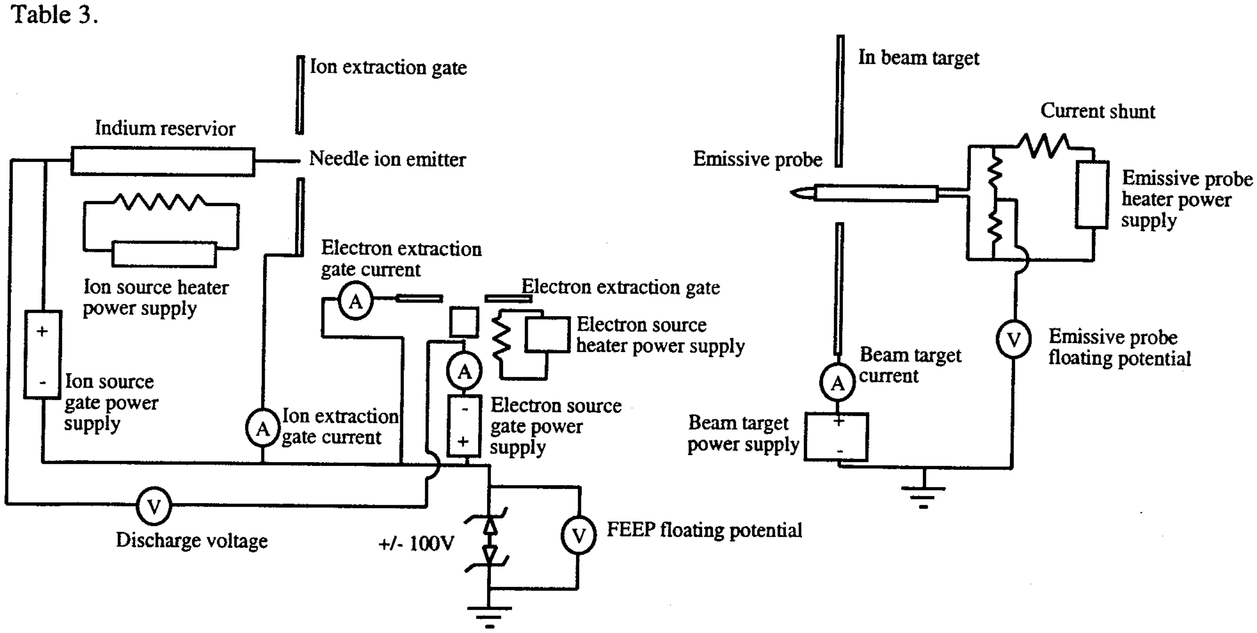
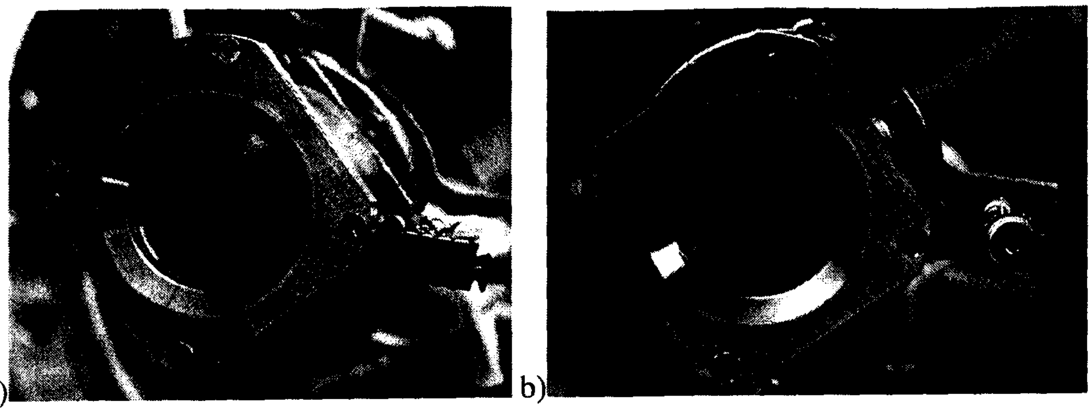


Figure 4. Electrical schematic employed in the In-FEEP and FE cathode compatibility experiments.



a) b)

Figure 5. In-FEEP with a) FEPET carbon-nanotube field emission cathode and b) SRI Int. Spindt-type field emission cathode.

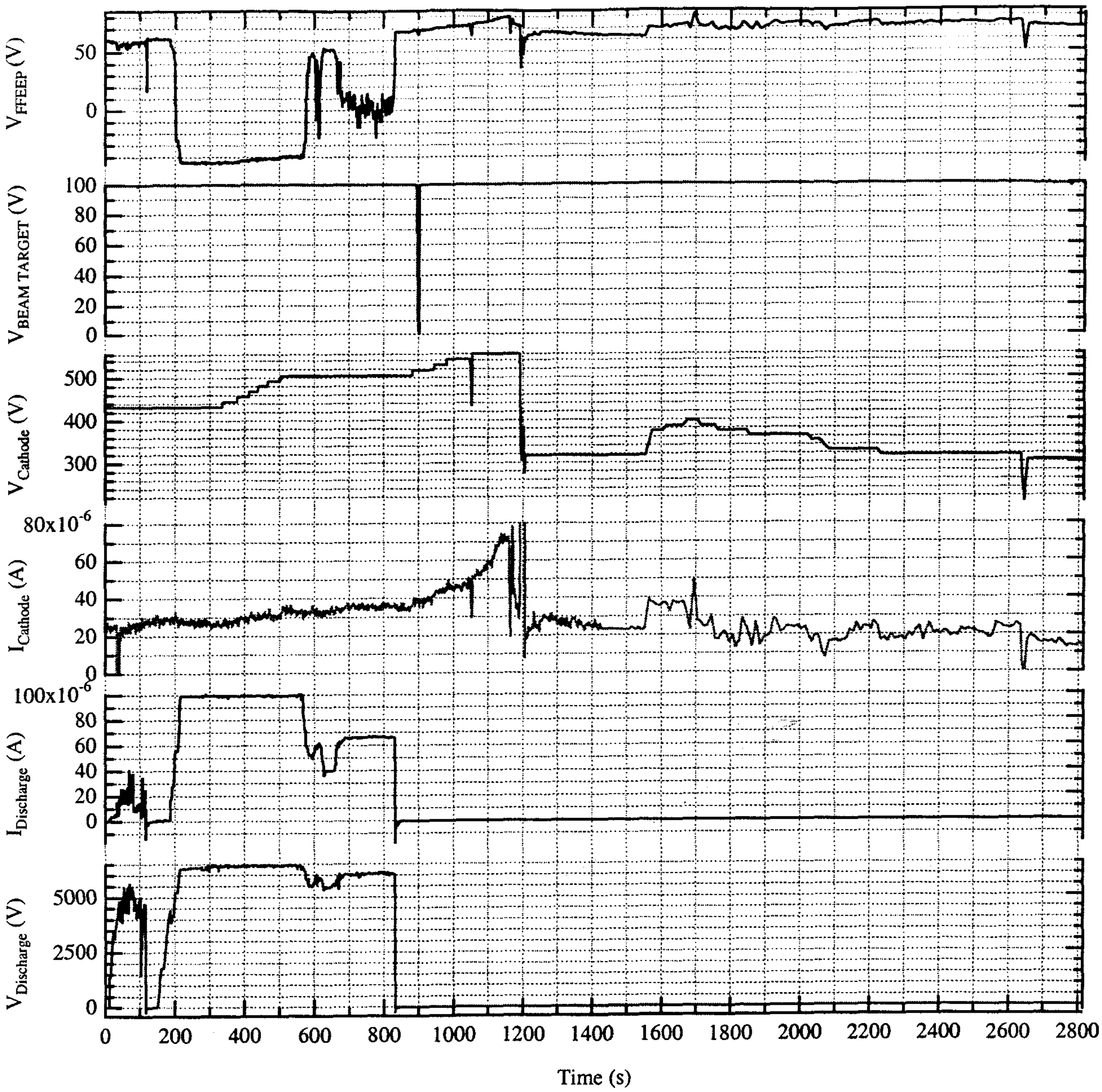


Figure 6. FEPET carbon-nanotube cathode and ARCS In-FEEP thruster currents, voltages, and floating potentials.

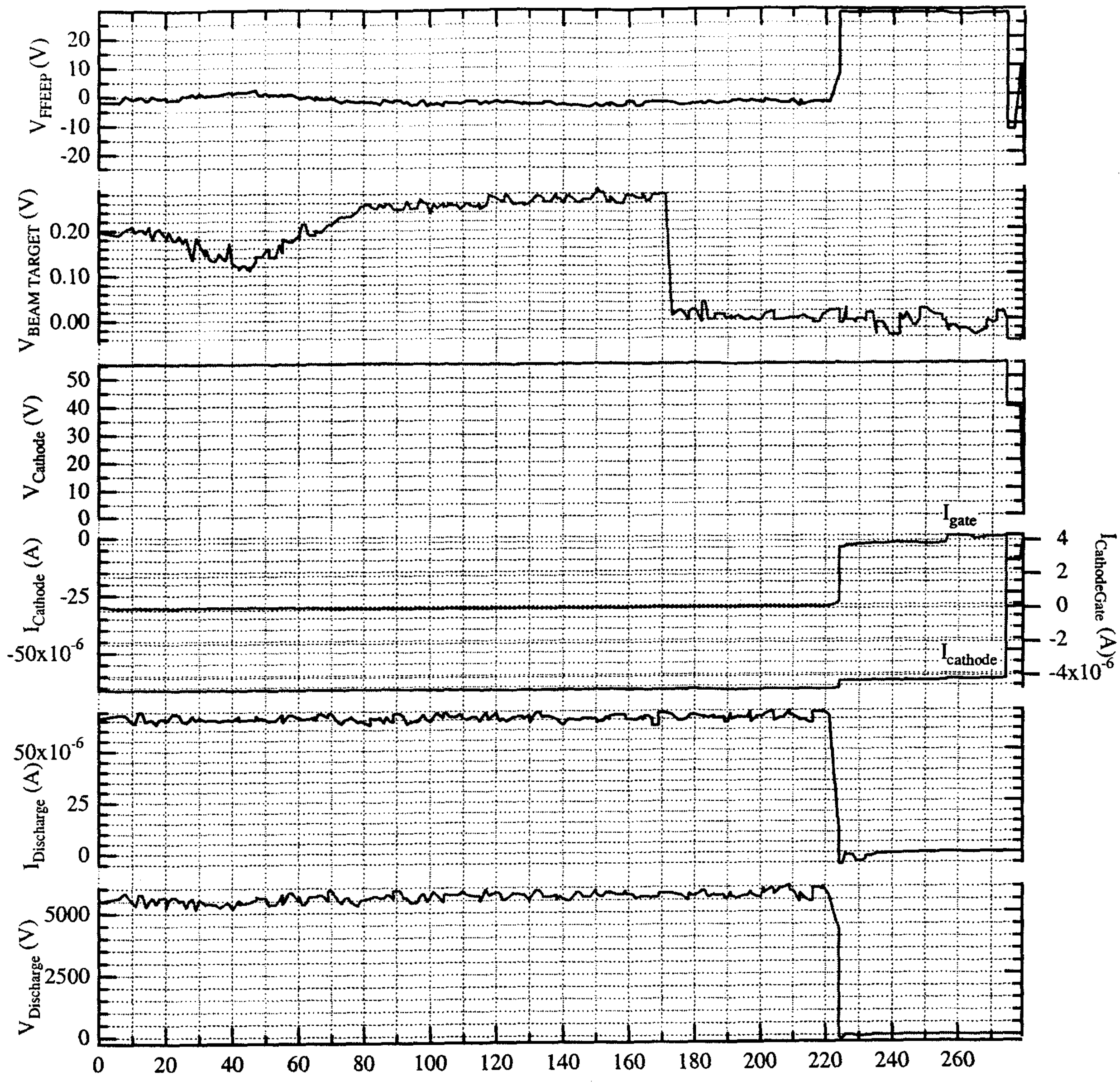


Figure 7. SRI Int. Mo field emission cathode and ARCS In-FEEP thruster currents, voltages, and floating potentials.

Table 3. In-FEEP thruster performance comparison with three different neutralizers.

Cathode	P_{ISH} **(W)**	P_{ISG} **(W)**	P_{ESG} **(W)**	P_{ESH} **(W)**	P_D **(W)**	P_Σ **(W)**	**T (μN)**	**P/T (W/μN)**
AEG-Thermionic	0.4 (0.04 A 10V)	0.002 (0.53 μA 6262 V)	?	1.575 (0.25A 6.3V)	0.75 98 μA 6268V	2.727	12.0	0.227
FEPET C arbon-nanotube Field emission	*0.4 (0.04A1 0V)*	*0.001 (0.2 μA 6374V)*	*0.245 (0.57 mA 432 V)*	*0*	*0.634 (99 μA 6406 V)*	*1.28*	*12.05*	*0.106*
SRI Int. Spindt-type	0.4 (0.04 A	0.001	5.4×10^{-6}	0	0.373	0.774	7.6	0.102

Field emission	10V)		0.1 μA 54 V		(66 μA 5652 V)			

CONCLUSIONS

The integration of FE cathodes and EP systems presents many challenges that are being addressed in a cathode development program. The cathode configuration required has been identified and is currently under development. The cathode material investigation is still underway to identify a material with the required oxidation resistance and work function. The results of preliminary experiments conducted show that EP and FE cathodes are compatible. Further experiments are required to identify the range of compatibility of these systems and further cathode development is required to improve cathode performance and lifetime in thruster environments.

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